

IRRADIANCE OR LUMINOSITY CHANGES?

Sabatino Sofia¹ and Linghuai H. Li^{1,2}¹Department of Astronomy, Yale University, New Haven, CT 06520, USA²Purple Mountain Observatory, Chinese Academy of Science, Nanjing, Jiangsu 210008, China

ABSTRACT

Whereas a variation of the solar luminosity, L , will inevitably cause a similar change of the total solar irradiance, S , the opposite is not true. In fact, the bulk of the days to months variations of S can be explained entirely in terms of the passage of active regions across the solar disk. In this case, L remains essentially unchanged.

For the total irradiance variation observed over the solar cycle, the issue is more uncertain. One view explains this modulation primarily as a combined action of active regions and magnetic network. These components would be superposed to an otherwise unchanging photosphere. the other view suggests that the activity cycle modulation of S is primarily produced by a variation of L (both in terms of R and T_{eff}) caused by structural reajustments of the interior of the Sun induced by a changing magnetic field. We will present evidence in support of this second interpretation, and a model for it. We will also present the S variations over the last 5 centuries implied by our model.

Key words: Solar interior; magnetic field; irradiance.

1. INTRODUCTION

There is no question that

- The hours to months variations of the total irradiance are primarily (totally?) due to active regions.
- The spots depress the irradiance.
- The faculae add to the irradiance.
- The contrasts are sufficiently high to be measured with some confidence.
- The temporal behavior during one rotation is exactly as expected.

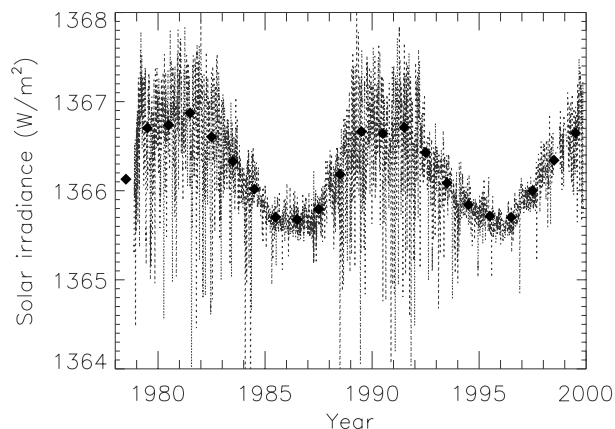


Figure 1. A composite solar irradiance record from the end of 1978 to the present (Fröhlich & Lean, 1998) and the yearly mean of solar irradiance.

However, it is not the case for the 11-year cycle, as shown in Figure 1 (Fröhlich & Lean, 1998).

- It is usually **assumed** that the magnetic network causes most of the modulation.
- The measured network contrast is insufficient to account for the entire variation (Ermolli et al., 2000).
- The precision of the irradiance measurements is less certain because instrument degradation is more significant than that in short timescales.
- Proxies of the network are designated, and their magnitude is adjusted to minimize residuals with observations.

From this viewpoint, it is assumed that the background photosphere remains unchanged during the entire cycle.

Of course, an alternative possibility is that most (if not all) of the 11 year variability is due to a change in the "luminosity" without the effects of the magnetic network. In order for that to happen, the following are true:

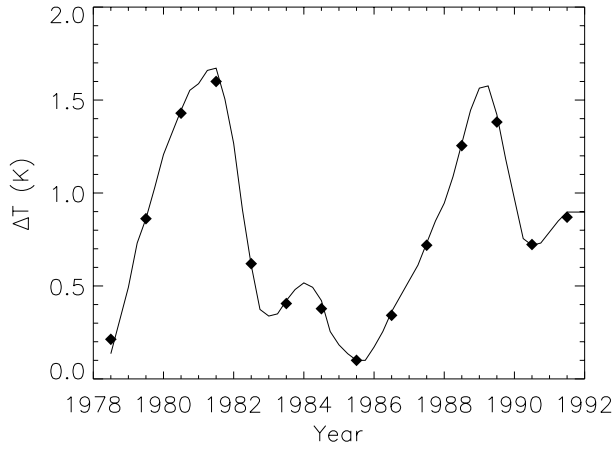


Figure 2. The measured solar photospheric temperature variations from 1978 to 1992 (Gray & Livingston, 1997) and the yearly mean.

- The photospheric temperature must change.
- The internal solar structure must change.
- The solar radius must change.

We propose here the explanation that the 11-year modulation of the total irradiance is due to structural adjustments of the solar interior in response to a variable internal magnetic field.

2. EVIDENCE IN SUPPORT OF SOLAR STRUCTURE VARIATIONS

2.1. Variations of solar effective temperature

The solar effective temperature was measured by Gray & Livingston (1997) from ratios of spectral line depths of

$$\text{CI}(\lambda 5380)/\text{FeI}(\lambda 5379)$$

and

$$\text{CI}(\lambda 5380)/\text{TiII}(\lambda 5381)$$

The excitation potentials of these lines are different from each other.

$$\text{CI} = 7.68 \text{ eV},$$

$$\text{FeI} = 3.69 \text{ eV},$$

$$\text{TiII} = 1.57 \text{ eV}.$$

The consistency of results indicates that the T_{eff} they measure is photospheric temperature. The spectroscopic temperature variations of the sun measured by Gray and Livingston (1997) over the period from 1978 to 1992, are shown in Figure 2. The zero point is chosen arbitrarily.

2.2. Variations of solar oscillations

Solar-cycle effects on solar oscillation frequencies were determined by Libbrecht and Woodard (1990). Recently, Bhatnagar et al. (1999) presented a correlation analysis of GONG p-mode frequencies with nine solar activity indices for the period from 1995 August to 1997 August. A decrease of $0.06 \mu\text{Hz}$ in frequency during the descending phase of solar cycle 22 and an increase of $0.04 \mu\text{Hz}$ in the ascending phase of solar cycle 23 are observed. These results provide the first evidence for change in p-mode frequencies around the declining phase of cycle 22 and the beginning of new cycle 23. This analysis further confirms that the temporal behavior of the solar frequency shifts closely follow the phase of the solar activity cycle. Besides, the analysis given by Howe et al. (1999) suggests that the solar cycle related variation of the oscillation frequencies is not due to contamination of observed Doppler shifts by the surface magnetic fields.

2.3. Radius variations

Ground-based measurements of the solar radius exist over three centuries, but the results are controversial and inconsistent. When a homogenized data base covering observations over the last three centuries is used, Basu (1998) found a statistically significant positive correlation between solar radius and sunspot numbers. Measurements of the solar radius made with the Danjon astrolabe at Santiago, Chile, and with the magnetograph of the solar telescope of Mount Wilson Observatory during the period 1990-1995, show similar variations in time and with a similar trend as the variation of sunspot numbers (Noël, 1997).

The space-based MDI-SOHO limb observations (Emilio et al., 2000) also show that the cycle variation of the solar radius is in phase with sunspot numbers. However, the estimated upper limit for the cycle variation is $\delta r_{\text{cycle}} = 21 \pm 3$ milliarcsec.

All the above are inconsistent with an unchanging solar interior and suggest changes within the solar interior.

3. METHOD

Several years ago, Endal et al. (1985) proposed that a variable internal magnetic field should affect all the global parameters of the sun. Subsequently, Lydon & Sofia (1995) carefully systematized the formulation of the problem, and wrote a code to do exploratory calculations. They found that sensible internal magnetic fields variations would perturb the internal structure of the sun, and consequently affect all global solar parameters.

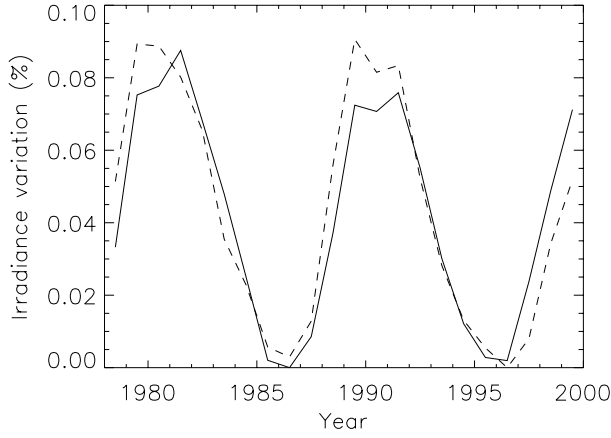


Figure 3. Comparison between the measured (solid curve) and calculated (dashed curves) solar irradiance variations.

The formulation and the code was further generalized by Li and Sofia (2000), and it is still being enriched at the present time. Elements of the new code are:

- Include the magnetic energy per unit mass χ , and the ratio of magnetic pressure to magnetic energy, $\gamma - 1$, as two additional variables in stellar structure and evolution.
- Take into account influence of magnetic fields on radiative opacities.
- Take into account all time-dependent contributions to the equations of stellar structure (we need short timescales).
- Modify the radiative loss assumption of a convective element to include local turbulence effects associated with small-scale magnetic fields.
- Use real equations of state on computing first and second order derivatives associated with magnetic fields.
- Use the most up-to-date stellar evolution codes (YREC7) since the effects we wish to determine are very small.

4. RESULTS

We use this code to show that the entire 11-year variations of the total irradiance (3) and T_{eff} (see Figure 4) could be produced by a magnetic field of strength (20-47 kG) and location ($r = 0.96R_{\odot}$) equal to that determined from helioseismology (Antia et al., 2000), as shown in Figure 5. Figure 6 shows the corresponding internal structure adjustment of the sun. The calculated cycle change of the solar radius is about $0''.02$, which is in agreement with the MDI/SOHO observation (Emilio et al., 2000).

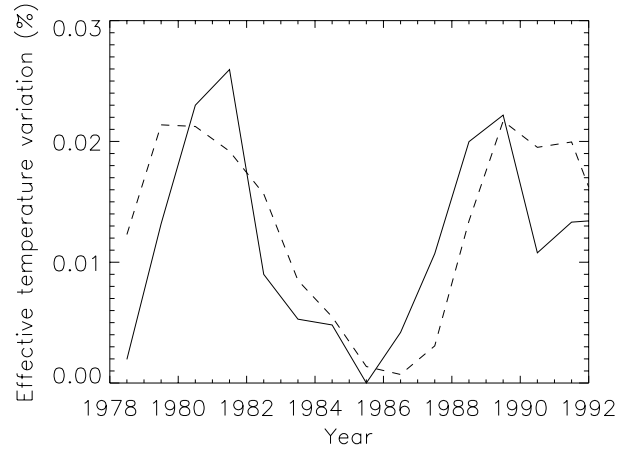


Figure 4. Comparison between the measured (solid curve) and calculated (dashed curve) solar photospheric temperature variations.

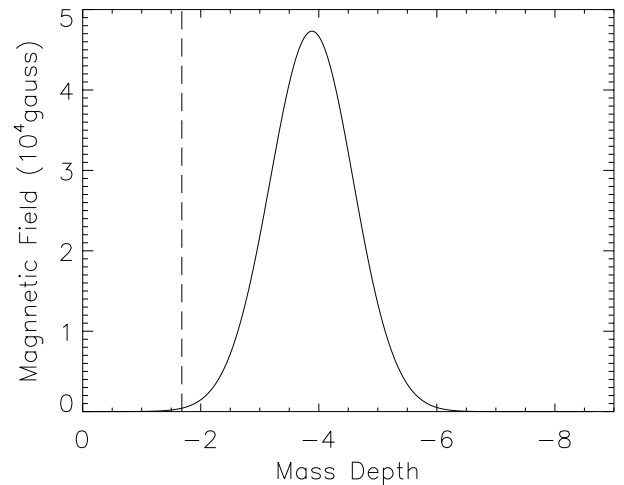


Figure 5. Distribution of the inferred magnetic field in the solar interior in 1989 according to the measured irradiance and photospheric temperature cyclic variations given in Figures 1 and 2. The vertical line indicates the base of the convection zone.

From this fit we find that the maximum magnetic field in the solar interior, B_m , is related to R_Z via

$$B_m = B_0 \{190 + [1 + \log_{10}(1 + R_Z)]^5\}, \quad (1)$$

where R_Z is the yearly-averaged sunspot number, $B_0 = 90$ G. The profile of the magnetic energy per unit mass χ is described by a gaussian function

$$\chi = \chi_m \exp\left[-\frac{1}{2}(M_D - M_{Dc})^2/\sigma^2\right], \quad (2)$$

where $M_{Dc} = -4.25$ specifies the location and $\sigma = 0.5$ specifies its width. B_m is used to determine χ_m . The mass depth M_D is defined as

$$M_D = \log_{10}(1 - M_r/M_{\odot}).$$

Using Eqs. (1) and (2), we can extrapolate the solar irradiance back during the period when the annual

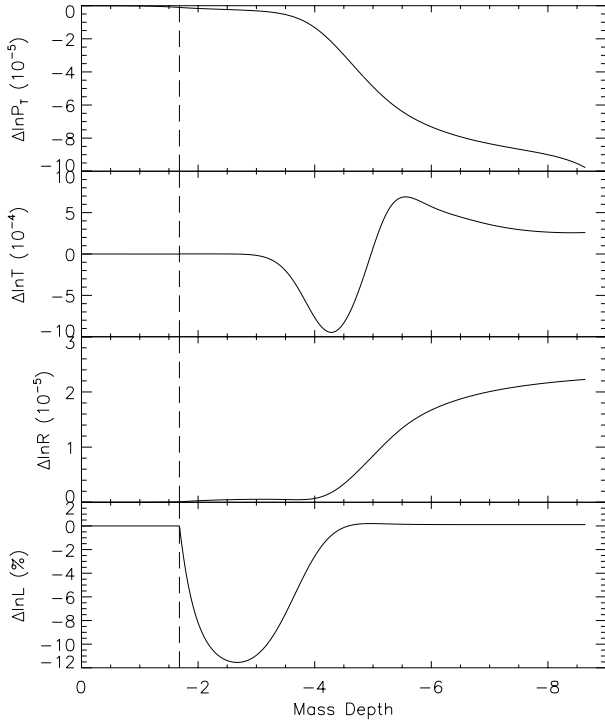


Figure 6. The structural changes caused by the magnetic field distributions given in Figure 5: relative pressure, temperature, radius and luminosity changes from top to bottom. The vertical line indicates the base of the convection zone.

sunspot numbers are available (Schöve, 1983; Hoyt & Schatten, 1998), as shown in Figure 7.

As we can see from Fig. 7, the maximum variability of the solar radius is about 2×10^{-5} , or 0.02 arc s. Although this variation is in agreement with the most recent determination of the cycle radius variations obtained from the MDI experiment on SOHO (Emilio et al., 2000), it is much smaller than the radius changes determined from historical data over the last 2 centuries. In our view, the most reliable historical data sets from which solar radius changes can be determined are the duration of total eclipses measured near the edges of totality. From them, changes of the order of 0.5 arc s have been detected. In particular, a change of 0.34 arc s between 1715 and 1979 (Dunham et al., 1980), a change of 0.5 arc s between 1925 and 1979 (Dunham et al., 1980), and no change between 1979 and 1976 (Sofia et al., 1983), were detected. If such changes are real, what could cause them? What are the corresponding solar irradiance changes?

If we use the magnetic field location required to produce the 11 year cycle variability, we find that it is impossible to produce a 0.5 arcsec radius variation even if we apply an unreasonably strong magnetic field. However, our model shows that the deeper the location of a magnetic field and the more intense the magnetic field, the larger the resulting radius change.

We thus compute the magnetic field required to pro-

duce the detected radius change between 1715 and 1979 as a function of mass depth, as displayed in the top panel in Fig. 8. It is well known that a strong magnetic field will cause a change of location of the boundary between the convective and the radiative region (Lydon & Sofia, 1995). The second panel from the top in this figure shows how the convection boundary R_{CZ} varies with the applied magnetic field (solid curve), and how the location of the maximal magnetic field, R_B , varies with the mass depth (dashed curve). The shaded region indicates the half-width of the required magnetic field. Of particular relevance are the values corresponding to the base of the convection zone, as indicated by the dot-dashed line in this figure, since all conventional dynamo models locate the process precisely at that depth. There, the magnetic field required to cause a 0.34 arcsec change of the solar radius is 1.3 million G, and the resulting luminosity variation is 0.12 percent (the third panel of Fig. 8), which is almost equally due to the variation of effective temperature (the bottom panel) and radius, since the radius variation contributes $2 \times \Delta \ln R = 0.07\%$. These values are interesting for producing significant climate change if the solar variations are sufficiently long lasting, and for not grossly contradicting what we know about the Sun, excepting a value for the magnetic field that is larger than we are comfortable with, but it is not in conflict with helioseismology (Antia et al., 2000; Sofia & Li, 2000).

5. CONCLUSIONS

From what we present above, we reach the following conclusions:

- The total irradiance variation, and the photospheric temperature variation observed over the 11-year activity cycle can be explained in terms of the variation of an internal solar magnetic field of 20-47 kG located at $r = 0.96R_{\odot}$.
- The above result is in agreement with helioseismological data, and with the variations of the solar radius measured with MDI/SOHO.
- The extrapolation of this process to the past 2-3 centuries produces a change in luminosity of only 0.1%, and a radius change of only 0.02 arcsec.
- If radius variations of order 0.5 arcsec do occur, a larger (1.3 MG) variation of a field located below the base of the convection zone is required.
- The combined effect of both phenomena can yield a ΔL of 0.2% over many decades.

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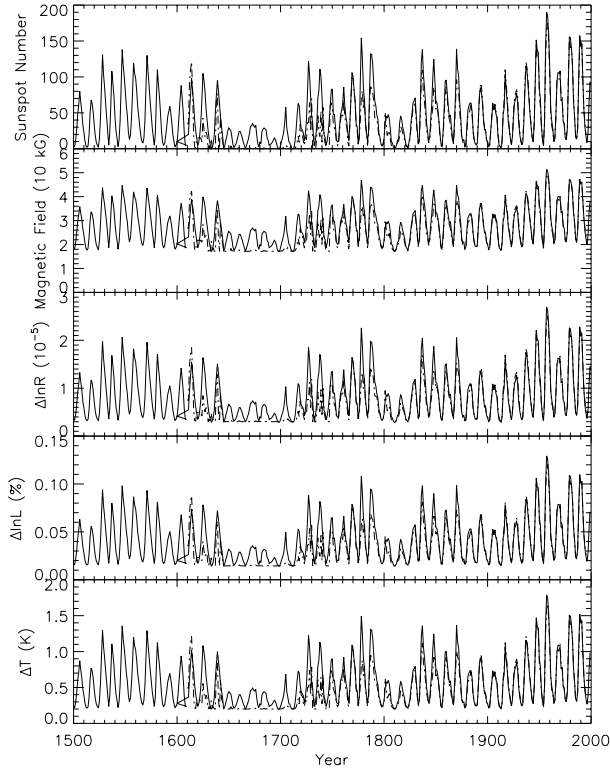


Figure 7. Solar variability in the past five centuries (solid curve corresponds to the Zürich sunspot number R_Z) and in the past four centuries (dashed curve corresponds to the group sunspot number R_G). kG stands for kilo-Gauss, L for total solar luminosity, T for solar effective temperature, R for solar radius.

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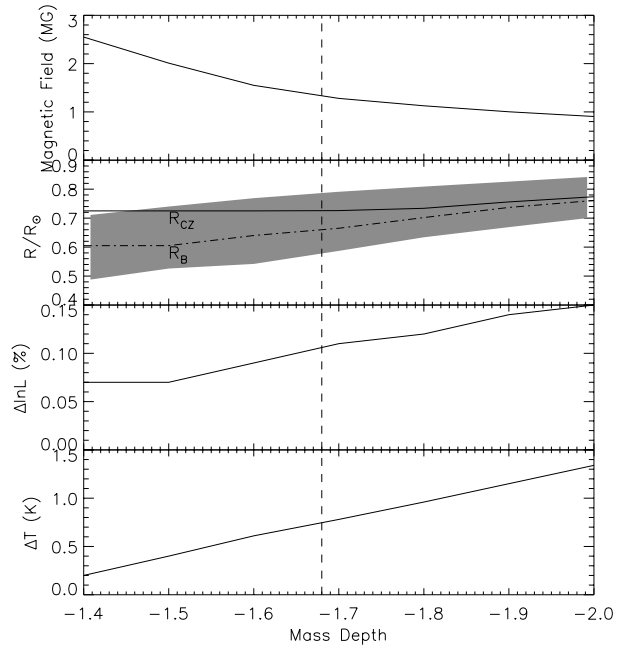


Figure 8. Solar variability corresponding to the probable change in the solar radius between 1715 to 1979. R_{CZ} is the location of the base of the convection zone, while R_B is the location of maximal magnetic field. MG stands for Million Gauss. The mass depth is defined as $\log(1 - M/M_\odot)$ by the mass coordinate M . The smaller the mass depth, the closer to the surface of the model sun.

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